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Soil structure and pedotransfer functions

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Summary

Accurate estimates of soil hydraulic properties from other soil characteristics using pedotransfer functions (PTFs) are in demand in many applications, and soil structural characteristics are natural candidates for improving PTFs. Soil survey provides mostly categorical data about soil structure. Many available characteristics such as bulk density, aggregate distribution, and penetration resistance reflect not only structural but also other soil properties. Our objective here is to provoke a discussion of the value of structural information in modelling water transport in soils. Two case studies are presented. Data from the US National Pedon Characterization database are used to estimate soil water retention from categorical field-determined structural and textural classes. Regression-tree estimates have the same accuracy as those from textural class as determined in the laboratory. Grade of structure appears to be a strong predictor of water retention at −33 kPa and −1500 kPa. Data from the UNSODA database are used to compare field and laboratory soil water retention. The field-measured retention is significantly less than that measured in the laboratory for soils with a sand content of less than 50%. This could be explained by Rieu and Sposito's theory of scaling in soil structure. Our results suggest a close relationship between structure observed at the soil horizon scale and structure at finer scales affecting water retention of soil clods. Finally we indicate research needs, including (i) quantitative characterization of the field soil structure, (ii) an across-scale modelling of soil structure to use fine-scale data for coarse-scale PTFs, (iii) the need to understand the effects of soil structure on the performance of various methods available to measure soil hydraulic properties, and (iv) further studies of ways to use soil–landscape relationships to estimate variations of soil hydraulic properties across large areas of land.

Introduction

Soil hydraulic properties have many potential users. In hydrology, soil water retention and transport characteristics are used to partition precipitation into runoff and infiltration and to assess evapotranspiration. In agronomy, the same data are used to schedule management practices, especially irrigation and chemical application. In meteorology, surface soil moisture is used to establish components of the heat balance. In contaminant hydrology and geochemistry, estimates of hydraulic properties in the vadose zone are essential for estimating contaminant transport. Soil hydraulic measurements are time-consuming and become impractical when hydrological estimates are needed for large areas. Generations of researchers have quantified and interpreted relationships between soil hydraulic properties and data available from soil survey. Terms such as 'predicting soil properties', 'estimating soil properties', and 'correlating soil properties' have been used interchangeably to name contents, procedures and results of such studies (van Genuchten & Leij, 1992; Pachepsky *et al.*, 1999). Bouma (1989) introduced the term pedotransfer functions (PTFs) for statistical regression equations, expressing relationships between soil properties. Pedotransfer functions are most commonly used to predict soil hydraulic characteristics, but soil chemical and biological characteristics have also been estimated. Several reviews on the development of PTFs and their use have been published (e.g. van Genuchten & Leij, 1992; Pachepsky *et al.*, 1999; Wösten *et al.*, 2001).

Soil texture has long been used to predict soil hydraulic properties. Clapp & Hornberger (1978) used soil textural classes to estimate hydraulic properties, but more detailed particle-size distributions have been shown to increase the accuracy of predictions (Schaap *et al.*, 1998). The accuracy of texture-based estimation is, however, limited. Table 1 shows the variation of water retention within textural classes in the

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Table 1 Water retention at two soil water potentials in samples from different textural classes. Data for 14 250 samples from the US National Pedon Characterization database (Soil Survey Staff, 1997)

Textural class	Number of samples	Volumetric water content[a] at −33 kPa	Volumetric water content[a] at −1500 kPa
Sand	318	0.134 (0.072)	0.044 (0.025)
Loamy sand	528	0.172 (0.092)	0.062 (0.034)
Sandy loam	2984	0.238 (0.086)	0.096 (0.041)
Loam	2138	0.296 (0.067)	0.138 (0.042)
Silt loam	2791	0.334 (0.064)	0.132 (0.042)
Silt	51	0.335 (0.065)	0.085 (0.037)
Sandy clay loam	754	0.282 (0.062)	0.163 (0.038)
Clay loam	1203	0.345 (0.057)	0.203 (0.041)
Silty clay loam	1301	0.366 (0.047)	0.209 (0.037)
Sandy clay	141	0.301 (0.055)	0.209 (0.036)
Silty clay	661	0.403 (0.050)	0.268 (0.042)
Clay	1380	0.414 (0.068)	0.284 (0.049)

[a]Averages, with standard deviations in parentheses.

data subset from the US National Pedon Characterization database. Although differences between average values in the classes are significant, the distributions of values overlap substantially. Large errors are often encountered when the average value for a textural class is used to estimate water retention of a soil from that class. A similar uncertainty exists in texture-based estimates of saturated hydraulic conductivity. Figure 1 shows the range of median values and differences between first and third quartiles of the hydraulic conductivity for about 1000 samples collected in the USA (Rawls *et al.*, 1998).

Soil structural characteristics can be used to improve estimates of soil hydraulic properties. The arrangement of soil particles in secondary units, and, more broadly, the multiscale hierarchy of distinct, naturally formed spatial units of soil, has been shown to affect soil hydraulic properties. By counting the lengths and widths of voids in detail, Anderson & Bouma (1973) estimated the saturated hydraulic conductivity, K_{sat}, of an argillic horizon of silt loam soil using the Kozeny–Karman equation for flows in slits. Rawls *et al.* (1993) used scaling of pore sizes to estimate the macropore K_{sat}. Lin *et al.* (1999) presented an elaborated system of morphometric indices and showed that these indices, rather than traditional texture, bulk density or organic matter content, appeared to be the best predictors of macro- and micropore flow. McKenzie *et al.* (1991) compared various sets of morphometric indices as hydraulic conductivity predictors. Although direct morphometry is undoubtedly an efficient way to characterize soil structure, it is costly and is not usually available from soil survey.

Soil structure is usually described using classes or categories rather than continuous variables. Such soil structure classes cannot be used directly in classical statistical regressions to estimate hydraulic properties from other soil properties.

Researchers use two approaches to incorporate soil structure in pedotransfer functions. The first is to use structural classes attributing an average class value to all soils in a class or developing regression equations separately for each group. Several sets of structural indices have been proposed to distinguish classes with distinctly different air porosity, available water capacities, and saturated hydraulic conductivities (Hall *et al.*, 1977; McKeague, 1987; Logsdon *et al.*, 1990). Williams *et al.* (1992) suggested using different equations to estimate water retention in weakly structured and well-structured soil horizons. With this approach, the challenge is to find an appropriate classification criterion and algorithm that would handle classed data. Another, much more common, approach is to use measurable continuous variables indirectly related to soil structure, such as bulk density or penetration resistance (see Wösten *et al.*, 2001, for a comprehensive review). However, such variables have a limited value because they do not uniquely define the spatial arrangement of structural units, which is a key factor affecting the ability of soil to retain and transmit water.

The hierarchical structure of soils poses a challenge for defining soil hydraulic properties *per se*. With a structural hierarchy, one should expect hydraulic properties to depend on scale. For example, the scale dependence of the dispersivity, as it is established in subsurface hydrology, arises from the way in which an individual solute particle will gradually

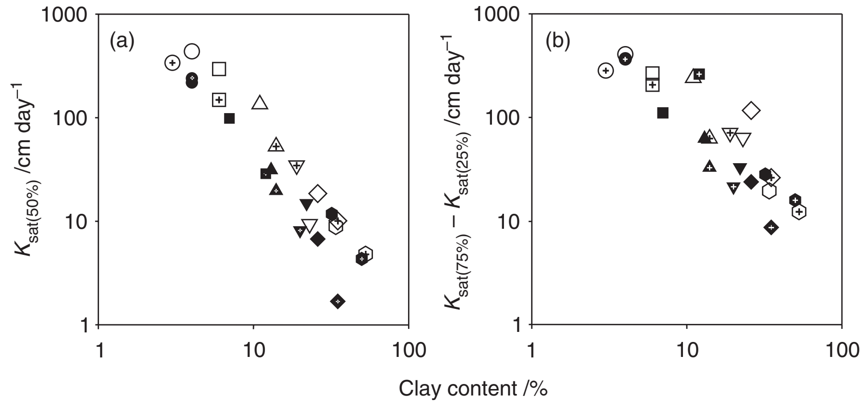

Figure 1 Saturated hydraulic conductivity, K_{sat}, grouped by textural classes and bulk density classes: (a) median values, $K_{sat(50\%)}$, for the groups; (b) difference between third, $K_{sat(75\%)}$, and first, $K_{sat(25\%)}$, quartiles of the distributions within each group; data for high and low bulk density samples are shown by filled and hollow symbols, respectively. ○/●, sand; ⊙/◉, fine sand; □/■, loamy sand; ⊞/⊞, loamy fine sand; △/▲, sandy loam; △/▲, fine sandy loam; ▽/▼, loam; ▽/▼, silt loam; ◇/◆, sandy clay loam; ◈/◈, clay loam; ⬡/⬢, silty clay loam; ⊕/⊕, clay.

experience more and more of the velocity fluctuations associated with the structural heterogeneity of an aquifer (Beven *et al.*, 1993). Examples of the dependence of saturated hydraulic conductivity on scale can be found in the literature (see Figure 2, for example, from Lauren *et al.*, 1988). An increase in the sample cross-section area leads to an increase in the saturated hydraulic conductivity in structured soils with macropores. Assuming the scaling law $K_{sat} = K_0(\text{cross-section area})^m$, one obtains the scaling exponents $m = 0.16$ for coarse-textured soil and $m = 0.32$ for fine-textured soil for the data in Figure 2.

The scale dependence of hydraulic properties may arise because the soil structural hierarchy has a scaling, i.e. its features repeat themselves at different resolutions. Then such scaling creates a physical basis for upscaling soil hydraulic properties. Rieu & Sposito (1991a,b) have developed the first model of fractal scaling in aggregation specifically for soils and soil-like materials, and have shown that their model can be used to predict both soil water retention and soil hydraulic conductivity.

Although we know that soil structure affects transport processes in soils, there are few quantitative applications of structural information to aspects of transport. We aim here to stimulate discussion by presenting two small case studies that relate soil structure to transport processes in soils.

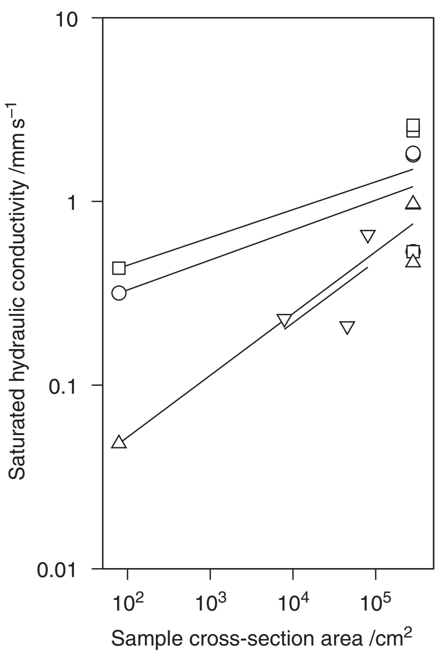

Figure 2 Examples of scale dependence in soil saturated hydraulic conductivity: ○, loamy sand, Ap horizon; □, loamy sand, A_2 horizon; △, sandy clay loam, B_1t horizon (Field *et al.*, 1984); ▽, clay loam, B_1t horizon (Lauren *et al.*, 1988). The lines show linear trends.

1. Estimating soil water retention from categorical textural and structural characteristics

Field descriptions of soil routinely include a structure characterization. So it would be useful to know whether and to what extent such structural properties may be used to predict soil hydraulic properties that are difficult to measure directly. In other words, how does coarse-scale soil structure reveal itself in fine-scale hydraulic properties? We can here address these questions using data from the US National Pedon Characterization database (Soil Survey Staff, 1997), as it contains many coupled data on soil structure and soil water retention at −33 and −1500 kPa.

Materials and methods

The US National Pedon Characterization database was screened to select soil samples that had (i) values of water contents at −33 kPa, θ_{33}, and −1500 kPa, θ_{1500}, measured on undisturbed clods, (ii) structure characterized by grade, size, and shape, and (iii) textural class determined in the field and from particle-size analysis in the laboratory. In all, 2140 samples were found. Mollisols, Aridisols, Alfisols, and Entisols are the most numerous soils in the data set, constituting 24, 14, 11, and 6%, respectively. Weak and moderate grade of structure are the most common in the set, whereas samples with the strong grade of structure constitute only 10%. Medium and fine sizes of structural units dominate. Angular blocky, blocky, and subangular blocky shapes are by far the most represented. No columnar, massive, or single grain structure shapes occur, and the wedge structure shape was found in only 14 samples. The most common textural class in the data set is silt loam (about 24% of all samples). Sandy loam, loam, clay, and silty clay loam are represented by 15, 12, 12, and 10% of all samples, respectively. Silt and sandy clay form less than 0.5% of all samples; sands and loamy sands each constitute about 3%.

Because the database includes both classified and numerical variables, we used the regression tree (Clark & Pregibon, 1992) for analysis with classed variables as predictors. The technique has been successfully used to explore databases in soil science (McKenzie & Jacquier, 1997). It is an exploratory technique based on uncovering structure in data, and partitions the samples to find both the best predictors and best grouping of samples. The resulting model partitions data first into two groups, then into four groups, and so on, providing groups as homogeneous as possible at each of the levels of partitioning. Each partitioning can be viewed as a branching, and the final fit of model to data looks like a tree with two branches originating from each node. We used the jackknife cross-validation to prune the regression tree to provide a trade-off between the number of branches and the accuracy of predictions based on the average within a group for all members of this group, as described by Clark & Pregibon (1992).

Results

The regression tree for water content at −33 kPa is shown in Figure 3. Field-determined structural and textural classes have been used as predictors. The first two divisions of samples are made by the textural class. The grade of structure is the most informative, followed by the size and the shape of structural units. A stronger grade usually increases water retention, as does a larger size of structural units. The root-mean-square error of predictions based on average within groups is $0.062\,m^3\,m^{-3}$, which is the same as for the estimates from the textural class as determined in the laboratory.

Grade of structure appears to be a fairly strong predictor of water retention. This characteristic describes the distinctness of the structural units in place, and the ease of separation into discrete units, as well as proportion of units that hold together when the soil is handled (Soil Survey Division Staff, 1993). The observed effect of grade on the average θ_{33} is similar to that reported for water retention at −10 kPa, θ_{10}, by several authors including Bouma (1992), who observed differences in water retention between weak and strong grade of structure in arable and grassed Haplaquents, respectively. Bouma found that the average water retention at −10 kPa was larger in samples with strong grade of structure, although this difference was not statistically significant. Soil with a weaker grade also had smaller water retention at −10 kPa in the study of Anderson & Bouma (1973), who compared the water retention of two fine silty mesic Argiudolls both having a medium prismatic structure that broke down to subangular blocky structural units. Shaw *et al.* (1997) compared pore size distributions for B_{tv} and B_t horizons in 18 pedons of fine loamy, siliceous, thermic Kandiudults with various contents of plinthite. Image analysis showed a much larger percentage of pores with the equivalent diameter between 0.05 and 0.005 cm in horizons with weak grade of structure as compared with horizons with the moderate grade of structure. This range of equivalent diameters corresponds to the range of matric potentials between −0.6 and −6 kPa, which means that horizons with a weak grade of structure lose much more water as the suction is applied than horizons with a moderate grade of structure. Southard & Buol (1988), studying Ultisols, noted that the grade of blocky structure gradually became stronger with increasing depth, whereas the proportion of pores emptying at −10 kPa decreased with depth. This implies an increase in water retention, since bulk density did not show depth-related trends.

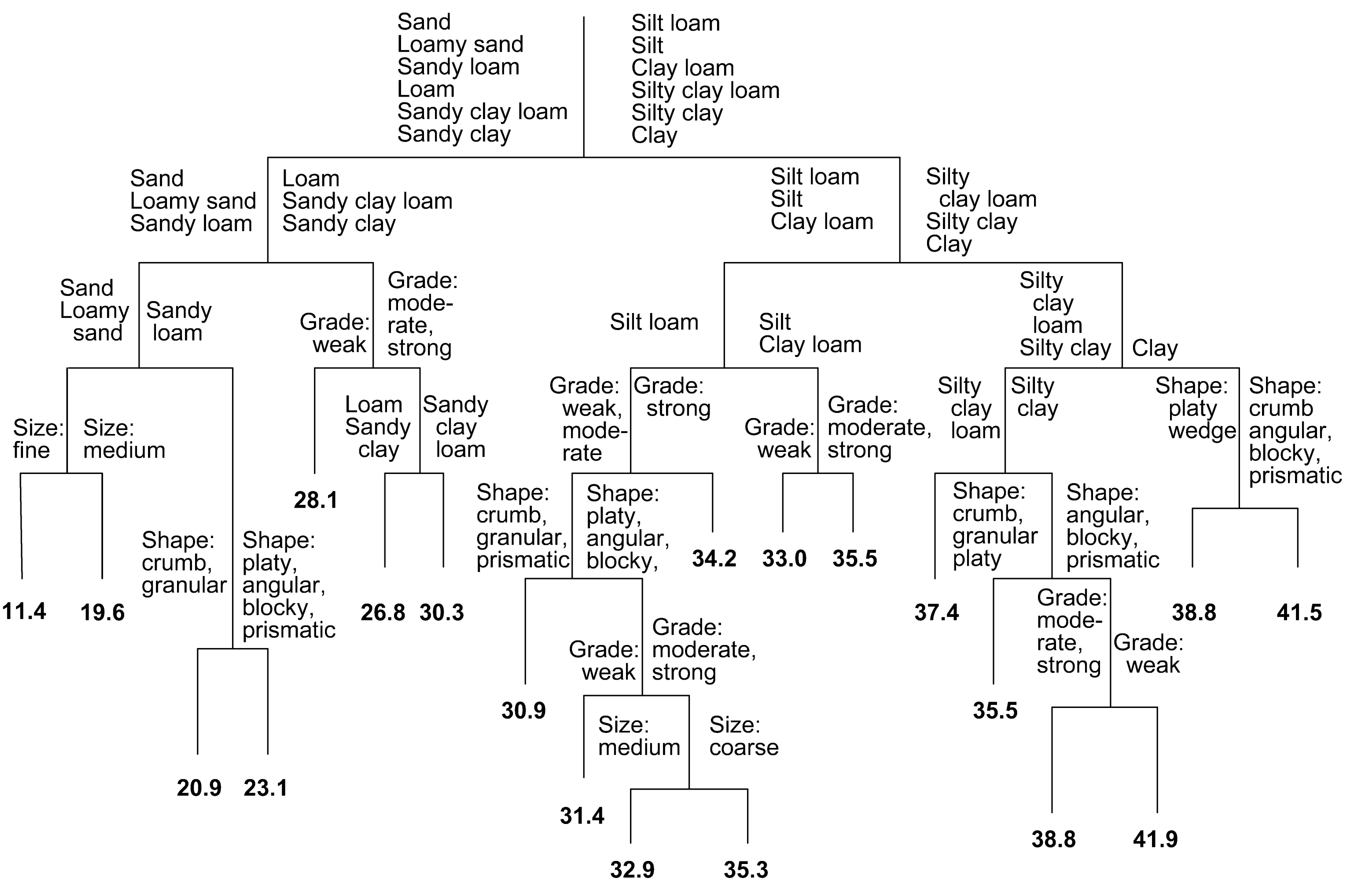

Figure 3 Regression tree to estimate water content at −33 kPa from soil textural and structural classes. Estimates for each group ($m^3\,m^{-3}$) are shown at the terminal nodes of the tree.

Although using structural classes does not radically improve the accuracy of predictions, it shows the potential of quantifying structure to explain hydraulic properties of a specific soil. In this way we have empirical evidence of the relation between structure observed at the scale of the soil horizon and structure at finer scales affecting water retention of soil clods.

2. Scale-related differences between laboratory and field water retention

Discrepancies between values of soil water retention measured in the field and in the laboratory have been reported in the literature. The differences between the two techniques were attributed to the poor depth resolution of the neutron probe (Parkes & Waters, 1980), to inadequate representation of large pores in the laboratory (Field *et al.*, 1984), to sample disturbance and spatial variation (Field *et al.*, 1984; Shuh *et al.*, 1988), to hysteresis or overburden pressure or both, and to scale effects related to the sample size (Shuh *et al.*, 1988). Pachepsky *et al.* (2001) showed that the differences between laboratory and field soil water retention in fine-textured soils could be explained by the scale dependence in soil's bulk density and closeness of gravimetric water contents in the field and laboratory.

The model of Rieu & Sposito (1991a) predicted scale dependence of bulk density and similar values of fractal dimensions derived from (i) 'aggregate bulk density–aggregate size' data and (ii) water retention. Filgueira *et al.* (1999) successfully tested these predictions in model systems of packed aggregates from loam and silt loam soils. We here test this theory for undisturbed soils using data from the UNSODA database (Leij *et al.*, 1996).

The data set

The UNSODA database was screened for coupled soil water retention data, from laboratory and field, measured during drying or drainage. This gave a data set in which sands, loamy sands, silt loams, and silty clay loams were well represented and constituted 21, 15, 18, and 15%, respectively, of all samples. Sandy loams, loams, sandy clay loams, and clay loams constituted 8, 7, 5, and 5%, respectively. Other textural classes were represented by one or two samples. Measurements were made by workers in seven countries. The laboratory samples were all undisturbed and of varied sizes. We used radii of equivalent spheres, R_L, that had the same volume as the laboratory sample, to compare these samples. Of all of the samples, 10% had R_L between 2.2 and 2.4 cm, 72% had R_L between 2.4 and 2.6 cm, 11% had $R_L = 2.9$ cm, and 7% had $R_L = 3.8$ cm. The water contents in the field were measured by neutron probe in all data sets, although in some cases these measurements were augmented by gravimetric sampling. Matric potential was measured with tensiometers in the field. Comparisons of water contents were made in the range of matric potentials where field and laboratory data overlapped. To make the comparisons, laboratory water contents were log-linearly interpolated to the matric potentials observed in the field.

Results

Field and laboratory volumetric water contents are compared in Figure 4. Coefficients of linear regressions of field water contents on laboratory ones at the same matric potentials are given in Table 2. Both random and deterministic components can be seen in the differences between the two sets of water contents. Coarse-textured soil horizons (mostly sands, loamy sands) have appreciable random differences between laboratory and field water retention values, but they show a small deterministic bias in the differences. The slope of the regression is slightly less than 1.0, and the intercept is only about $0.03\,\mathrm{m^3\,m^{-3}}$ (Table 2). The fine-textured soil horizons with sand content less than 50% have a random component in the differences between field water and laboratory water contents that is similar to the one in coarse-textured soils. These soils also have definite bias, and field water contents are substantially smaller than the laboratory values (Figure 4 and Table 2). Soil horizons of intermediate texture, with sand contents between 50% and 80%, also show the bias but it is not as large as that for the fine-textured horizons.

A fractal scaling of the bulk density may explain the deterministic component of the observed 'field–laboratory' differences in volumetric water contents in the range of large water contents. In this model of soil, the bulk density, ρ, depends on scale R as (Rieu & Sposito, 1991a):

$$\rho = aR^{D_m - 3}, \tag{1}$$

where D_m is the mass fractal dimension, $2 < D_m < 3$. Therefore, the ratio of bulk densities at field and laboratory scales, ρ_F and ρ_L, depends on the ratio of the corresponding sample radii, R_F and R_L, as

$$\frac{\rho_L}{\rho_F} = \left(\frac{R_F}{R_L}\right)^{3-D_m}. \tag{2}$$

If the gravimetric water contents are the same for a given soil water matric potential, then the ratio of the volumetric water contents, θ_L/θ_F, is the same as the ratio of bulk densities. Values of D_m found from the laboratory water retention data vary mostly between 2.85 and 2.95 in most soils (Rieu & Perrier, 1994). The equivalent radii of laboratory samples, R_L, are mostly between 2.2 and 2.9 cm, and the average radius of the neutron probe volume is $R_F = 15$ cm in wet soil in the field. Therefore, we find that the ratio of bulk densities in field and laboratory samples, ρ_L/ρ_F, may vary mostly between $(15/2.9)^{0.05}$ and $(15/2.2)^{0.15}$, i.e. between 1.09 and 1.33. The 25% and 75% quartiles for the distribution of ratios θ_L/θ_F that can be seen in Figure 4 for the fine-textured soils are

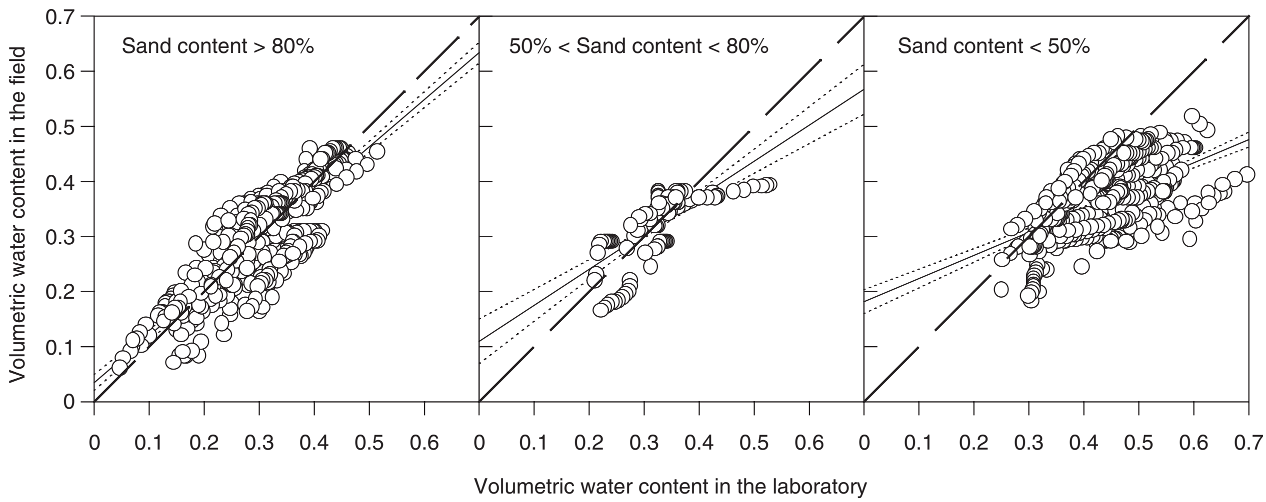

Figure 4 Relationship between field and laboratory water contents at the same soil water matric potential for three textural groups. Linear regression trends, 95% probability confidence intervals, and one-to-one line are shown with solid, dotted, and dashed lines, respectively.

1.06 and 1.33, respectively. These values are close to the ones predicted theoretically by Rieu & Sposito.

The scaling given in Equation (2) and the values of D_m used above are derived from the data on soil water retention in the capillary range and from those on the aggregate bulk density. If this scaling is valid at scales well in excess of the capillary pore and aggregate size then the scaling is applicable in the range of scales between the laboratory sample size and the neutron probe sensitivity range. That may not necessarily be true, as fractal scaling in soils tends to be valid within a range of scales not exceeding 1–1.5 orders of magnitude (Giménez *et al.*, 1997). In coarse-textured soil, water retention curves change their slopes abruptly at the air-entry point. Therefore, the scaling with a fractal dimension of 2.85–2.95 found from water retention curves apparently ceases at coarser scales. This may be the reason for a relatively small average difference between field and laboratory water retention in these soils. In fine-textured soil, the air-entry point is difficult to define as there is no abrupt change in the slope of the water retention curve, and the scaling found in the capillary range may extend to the range of scales that includes the size of the field neutron probe sensitivity volume.

The bulk density scaling, as a hypothetical explanation of the differences between field and laboratory retention data, does not discount the importance of other field factors contributing to these differences. These factors have probably played some role in the studies that provided data for this work. However, the hierarchy of soil structure seems to play a substantial role in differences between soil water retention in the laboratory and that in the field. Those differences are significant in fine-textured soil in which such a hierarchy is most often observed. The presence of such a hierarchy may be the reason for assigning different values of soil water potential to water contents at field capacity. Values of −10 and −30 kPa are often used for coarse- and fine-textured soils, respectively. Those values have been derived from comparison of water

Table 2 Parameters of linear regressions of water contents measured in the laboratory on water contents measured in the field at the same matric potentials

	Sand > 80% (sand, some loamy sands)	50% < Sand < 80% (some loamy sands, most sandy loams, sandy clay loams and sandy clays)	Sand < 50% (loams, silt loams, silty clay loams, clays)
Regression parameters			
Slope[a]	0.857 (0.023)	0.655 (0.061)	0.427 (0025)
Intercept[a]	0.034 (0.007)	0.110 (0.021)	0.179 (0.011)
Laboratory water content range /m^3 m^{-3}			
Maximum	0.515	0.529	0.722
Minimum	0.048	0.211	0.251

[a]Estimated average, with standard errors in parentheses.

content data from field and laboratory. Larger values of soil water potential had to be used to equate laboratory water retention and field water content in fine-textured soils. Data in Figure 4 show that there may be a common approximate value of the field capacity potential for soils of all textures.

The observed differences between the results from field and laboratory have important consequences for estimating soil hydraulic properties from readily available soil data. Pedotransfer functions are built from the laboratory data on water retention. Estimates of the available water capacity in soil horizons obtained from such pedotransfer functions may be too large. Figure 4 and Table 2 show that a correction needs to be applied to such estimates.

Discussion and conclusions

Both structural information and the notion about the existence of structural hierarchy *per se* are useful to estimate hydraulic properties. We found it remarkable that qualitative morphological observations of soil *in situ* could be translated into quantitative soil hydraulic parameters as shown in Figure 3. Field studies describe peds, such as blocks, columns, granules, plates, or prisms, that are formed by natural processes. If there is a hierarchy of soil structure, ped properties can be reflected in the structure of pore space in fairly small, undisturbed soil samples used for water retention measurements.

The usefulness of grade of structure as a predictor of water retention indicates a potential for observed aggregate-size distributions to be used in PTFs. Aggregate-size distributions have rarely been used as predictors of soil hydraulic properties (Wösten *et al.*, 2001). One reason may be that some mechanical breakage is involved in the aggregate-size analysis, and therefore not only structural but also mechanical properties of soils are reflected in aggregate size, number, and mass distributions. Defining grade class also involves some disturbance of the soil, and the grade of structure is determined by the distinctness of individual peds and the relationship of cohesion within peds to adhesion between units (Soil Survey Division Staff, 1993). Those properties also affect the results of the aggregate-size analysis, and therefore using aggregate-size distributions in pedotransfer functions could be worthwhile. Nimmo (1997) used grade-related parameters in a model of soil water retention with explicit formulation of structure effects. The results of Rieu & Sposito (1991b) show the applicability of scaling laws to properties of aggregates in soils. Such laws, where applicable, may provide a small number of parameters of the 'aggregate property–size' distributions to be tested as PTF inputs. Developments in scaling models of porosity formed by both aggregates and primary particles (Bird & Perrier, 2003) could indicate useful new parameters of soil structure and texture to use in estimating soil hydraulic properties.

One of the effects of scale or spatial resolution on the development of pedotransfer functions is that different characterizations of soil hydraulic properties are used at different scales. The complete water retention curve may be of interest in column studies and in studies on plots and lysimeters where the Richards equation is applied. However, crop models applied in the field often use the water-holding capacity of separate soil horizons as a leading soil hydraulic property (e.g. Ritchie *et al.*, 1999). Regional models often use the average water-holding capacity of soil profiles (e.g. Houser *et al.*, 1998). Many other scale-specific soil hydraulic properties can be found in models of crops and water balance. Properties related to the availability of water to plants in the CERES family of crop models, such as lower and upper level of available water, are also estimated. The evaporation coefficient is yet another example of a scale-specific hydraulic parameter for which a PTF could be developed (Boisvert & Dyer, 1987). The coarser the scale, the less is the information available to build pedotransfer functions. The models of scaling initiated by Rieu & Sposito (1991a) may help to shed light on scale-dependent changes of soil hydraulic properties as shown in Figure 4. This would lead to the use of the databases and PTFs of data at fine resolution to estimate hydraulic parameters for coarser scales.

The reliability of PTFs may be limited by the differences in methods used to measure soil hydraulic properties, which in turn may have profound effects on results. We have very little quantitative knowledge about the effect of soil structure on the variation in measurements of soil hydraulic properties obtained by different methods, although conceptually such an effect can be envisaged and models of scaling and hierarchy in soil structure may be able to predict it.

Coarse-resolution projects use estimates of hydraulic properties for large spatial units and require estimates of the variability of soil hydraulic properties within such units for uncertainty and risk analyses. The structure of soil cover along with soil structure becomes an important factor in the estimates of variability. Vachaud *et al.* (1988) pioneered the use of scaling to simulate spatial variability of soil hydraulic properties and relating scaling parameters to soil texture to produce a PTF. Soil texture, organic matter content, and bulk density are known to reflect both landscape position and land surface shape (Kreznor *et al.*, 1989; Paydar & Cresswell, 1996). Because these soil properties are most often included in PTFs, one can speculate that soil hydraulic properties should have some relationship to landscape position and land surface shape. Therefore, topographic variables have the potential to predict a deterministic component in variations of soil hydraulic properties across large areas of land for a wide range of scales (McKenzie & Ryan, 1999; Rawls & Pachepsky, 2002). The structure of soil cover has scaling properties (Ibáñez *et al.*, 1995), and such scaling may also be used to develop estimates of spatial variability in soil hydraulic properties.

Quantitative characterization of soil structure remains a challenge in spite of the advances in simulating its dynamic nature (Garnier *et al.*, 1997). Nevertheless, as proofs of the importance of soil structure characterization accumulate, more progress can be expected. Accurate estimates of soil hydraulic properties are in demand in many applications, and the modelling of soil structure across scales for predicting soil hydraulic properties is needed.

In the first part of this study we showed that structural information from the horizon scale can be used to explain water retention at finer scales. In the second part we demonstrated that the fine-scale structural information can be used to explain water retention at the scale of soil horizon. Because water retention itself reflects structure of the pore space in the soil, our work shows empirical evidence of relationships between structure at different scales. Across-scale modelling of soil structure can help to incorporate information on structure in pedotransfer functions to improve their accuracy and applicability.

Acknowledgements

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References

Anderson, J.L. & Bouma, J. 1973. Relationships between saturated hydraulic conductivity and morphometric data of an argillic horizon. *Soil Science Society of America Proceedings*, **37**, 408–413.

Beven, K.J., Henderson, D.E. & Reeves, A.D. 1993. Dispersion parameters for undisturbed partially saturated soil. *Journal of Hydrology*, **143**, 19–43.

Bird, N.R.A. & Perrier, E.M.A. 2003. The pore–solid fractal model of soil density scaling. *European Journal of Soil Science*, **54**, 467–476.

Boisvert, J. & Dyer, J.A. 1987. Le coefficient de sol dans les modèles empiriques de bilan hydrique. *Canadian Agricultural Engineering*, **29**, 7–14.

Bouma, J. 1989. Using soil survey data for quantitative land evaluation. *Advances in Soil Science*, **9**, 177–213.

Bouma, J. 1992. Effect of soil structure, tillage, and aggregation upon soil hydraulic properties. In: *Interacting Processes in Soil Science* (eds R. Wagenet, J.P. Baveye & B.A. Stewart), pp. 1–36. Lewis Publishers, Boca Raton, FL.

Clapp, R.B. & Hornberger, G.M. 1978. Empirical equations for some soil hydraulic properties. *Water Resources Research*, **14**, 601–604.

Clark, L.A. & Pregibon, D. 1992. Tree-based models. In: *Statistical Models in S* (ed. T.J. Hastie), pp. 377–419. Wadsworth, Pacific Grove, CA.

Field, J.A., Parker, J.C. & Powell, N.L. 1984. Comparison of field- and laboratory-measured and predicted hydraulic properties of a soil with macropores. *Soil Science*, **138**, 385–396.

Filgueira, R.R., Pachepsky, Y.A., Fournier, L.L., Sarli, G.O. & Aragón, A. 1999. Comparison of fractal dimensions estimated from aggregate mass–size distribution and water retention scaling. *Soil Science*, **164**, 217–223.

Garnier, P., Rieu, M., Boivin, P., Vauclin, M. & Baveye, P. 1997. Determining the hydraulic properties of a swelling soil from a transient evaporation experiment. *Soil Science Society of America Journal*, **61**, 1555–1563.

Giménez, D., Perfect, E., Rawls, W.J. & Pachepsky, Y. 1997. Fractal models for predicting soil hydraulic properties: a review. *Engineering Geology*, **48**, 161–183.

Hall, D.G.M., Reeve, M.J., Thomasson, A.I. & Wright, V.F. 1977. *Water Retention, Porosity and Density of Field Soils*. Soil Survey Technical Monograph No 9, Rothamsted Experimental Station, Harpenden.

Houser, P.R., Shuttleworth, W.J., Famiglietti, J.S., Gupta, H.V., Syed, K.H. & Goodrich, D.C. 1998. Integration of soil moisture remote sensing and hydrologic modeling using data assimilation. *Water Resources Research*, **34**, 3405–3420.

Ibáñez, J.J., De Alba, S., Bermúdez, F.F. & García-Álvarez, A. 1995. Pedodiversity: concepts and measures. *Catena*, **24**, 215–242.

Kreznor, W.R., Olson, K.R., Banwart, W.L. & Johnson, D.L. 1989. Soil, landscape, and erosion relationships in a Northwest Illinois watershed. *Soil Science Society of America Journal*, **53**, 1763–1771.

Lauren, J.G., Wagenet, R.J., Bouma, J. & Wösten, J.H.M. 1988. Variability of saturated hydraulic conductivity in a Glossaquic Hapludalf with macropores. *Soil Science*, **145**, 20–28.

Leij, F.J., Alves, W.J., van Genuchten, M.T. & Williams, J.R. 1996. *Unsaturated Soil Hydraulic Database, UNSODA 1.0 User's Manual*. EPA Report EPA/600/R-96/095, US Environmental Protection Agency, Ada, OK.

Lin, H.S., McInnes, K.J., Wilding, L.P. & Hallmark, C.T. 1999. Effects of soil morphology on hydraulic properties. II. Hydraulic pedotransfer functions. *Soil Science Society of America Journal*, **63**, 955–961.

Logsdon, S.D., Allmaras, R.R., Wu, L., Swan, J.B. & Randall, G.W. 1990. Macroporosity and its relation to saturated hydraulic conductivity under different tillage practices. *Soil Science Society of America Journal*, **54**, 1096–1101.

McKeague, J.A. 1987. Estimating air porosity and available water capacity from soil morphology. *Soil Science Society of America Journal*, **51**, 148–152.

McKenzie, N.J. & Jacquier, D.W. 1997. Improving the field estimation of saturated hydraulic conductivity in soil survey. *Australian Journal of Soil Research*, **35**, 803–825.

McKenzie, N.J. & Ryan, P.J. 1999. Spatial prediction of soil properties using environmental correlation. *Geoderma*, **89**, 67–94.

McKenzie, N.J., Smetten, K.R.J. & Ringrose-Voase, A.J. 1991. Evaluation of methods for inferring air and water properties of soils from field morphology. *Australian Journal of Soil Research*, **29**, 587–602.

Nimmo, J.R. 1997. Modeling structural influences on soil water retention. *Soil Science Society of America Journal*, **61**, 712–719.

Pachepsky, Y.A., Rawls, W.J. & Timlin, D.J. 1999. The current status of pedotransfer functions: their accuracy, reliability, and utility in field- and regional-scale modeling. In: *Assessment of Non-Point Source Pollution in the Vadose Zone* (eds D.L. Corwin, K. Loague & T.H. Ellsworth), pp. 223–234. Geophysical Monograph No 108, American Geophysical Union, Washington, DC.

Pachepsky, Y., Rawls, W.J. & Giménez, D. 2001. Comparison of soil water retention at field and laboratory scales. *Soil Science Society of America Journal*, **65**, 460–462.

Parkes, M.E. & Waters, P.A. 1980. Comparison of measured and estimated unsaturated hydraulic conductivity. *Water Resources Research*, **16,** 749–754.

Paydar, Z. & Cresswell, H.P. 1996. Water retention in Australian soils. II. Prediction using particle size, bulk density and other properties. *Australian Journal of Soil Research*, **34,** 679–693.

Rawls, W.J. & Pachepsky, Y.A. 2002. Using field topographic descriptions to estimate soil water retention. *Soil Science*, **167,** 223–235.

Rawls, W.J., Brakensiek, D.L. & Logsdon, S.D. 1993. Predicting saturated hydraulic conductivity utilizing fractal principles. *Soil Science Society of America Journal*, **57,** 1193–1197.

Rawls, W.J., Giménez, D. & Grossman, R. 1998. Use of soil texture, bulk density and slope of the water retention curve to predict saturated hydraulic conductivity. *Transactions of the American Society of Agricultural Engineers*, **41,** 983–988.

Rieu, M. & Perrier, E. 1994. Modélisation fractale de la structure des sols. *Comptes Rendus de l'Académie d'Agriculture*, **80,** 21–39.

Rieu, M. & Sposito, G. 1991a. Fractal fragmentation, soil porosity, and soil water properties. I. Theory. *Soil Science Society of America Journal*, **55,** 1231–1238.

Rieu, M. & Sposito, G. 1991b. Fractal fragmentation, soil porosity, and soil water properties. II. Applications. *Soil Science Society of America Journal*, **55,** 1239–1244.

Ritchie, J.T., Gerakis, A. & Suleiman, A. 1999. Simple model to estimate field-measured soil water limits. *Transactions of the American Society of Agricultural Engineers*, **42,** 1609–1614.

Schaap, M.G., Leij, F.L. & van Genuchten, M.T. 1998. Neural network analysis for hierarchical prediction of soil hydraulic properties. *Soil Science Society of America Journal*, **62,** 847–855.

Shaw, J.N., West, L.T., Truman, C.C. & Radcliffe, D.E. 1997. Morphologic and hydraulic properties of soils with water restrictive horizons in the Georgia Coastal Plain. *Soil Science*, **162,** 875–885.

Shuh, W.M., Cline, R.D. & Sweeney, M.D. 1988. Comparison of a laboratory procedure and a textural model for predicting in situ water retention. *Soil Science Society of America Journal*, **52,** 1218–1227.

Soil Survey Division Staff 1993. *Soil Survey Manual*. USDA Handbook No 18, US Government Printing Office, Washington, DC.

Soil Survey Staff 1997. *National Characterization Data*. Soil Survey Laboratory, National Soil Survey Center, Natural Resources Conservation Service, Lincoln, NE.

Southard, R.J. & Buol, S.W. 1988. Subsoil blocky structure formation in some North Carolina Paleudults and Paleaquults. *Soil Science Society of America Journal*, **52,** 1069–1076.

Vachaud, G., Vauclin, M. & Balabanis, P. 1988. Stochastic approach to soil water flow through the use of scaling factors: measurements and simulations. *Agricultural Water Management*, **13,** 249–261.

Van Genuchten, M.T. & Leij, F. 1992. On estimating the hydraulic properties of unsaturated soils. In: *Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils* (eds M.T. van Genuchten, F.J. Leij & L.J. Lund), pp. 1–14. University of California, Riverside, CA.

Williams, J., Ross, P. & Bristow, K. 1992. Prediction of the Campbell water retention function from texture, structure, and organic matter. In: *Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils* (eds M.T. van Genuchten, F.J. Leij & L.J. Lund), pp. 427–442. University of California, Riverside, CA.

Wösten, J.H.M., Pachepsky, Y.A. & Rawls, W.J. 2001. Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics. *Journal of Hydrology*, **251,** 123–150.